Phase-resolved correlation and its application to analysis of low-coherence interferograms

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A new signal-processing technique is proposed that involves a phase-resolved correlation method that one can use to determine the phase distribution of low-coherence interferograms. This method improves the sensitivity and resolution of low-coherence interferometers. The depth structure of an aluminum oxide–coated aluminum mirror was determined by use of a low-coherence interferometer with this method. Three signal peaks were successfully extracted from a noisy interferogram. © 2001 Optical Society of America

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A number of phase-oriented signal-processing methods, including the use of moire images, interference fringes, and interferograms, have been widely investigated for signals with carrier frequencies. Phase shifting and the Fourier-transform method are among the most commonly used methods applied to this kind of analysis, as they can extract the carrier's phase distribution from a signal and thus improve its signal-to-noise ratio (SNR).

Nondestructive, high-sensitivity profilometry techniques, such as white-light interferometry and optical coherence tomography, have been applied in various fields, including industrial processing and biomedical applications. However, phase-oriented signal-processing methods have seldom been employed, although they clearly have potential for developing good SNRs. The reason is that the phase-shifting method demands carrier phase shifting with respect to the envelope of an interferogram of fringe image. However, in most cases of interferogram analysis the Fourier-transform method does not give good results because of the single sinusoidal wave model assumed for the interferogram (a usual interferogram is expressed as a summation of sinusoidal waves).

Fourier-transform profilometry assumes that the signal that is analyzed has only one phase-modulated carrier, although in reality an interferogram is the sum of several independent signals, each with a different carrier phase.

We introduce a novel signal-processing method for analyzing interferograms that is based on phase-resolved correlation in which a one-dimensional interferogram is resolved into a three-dimensional intensity distribution in position-frequency phase space. Each independent signal peak in one interferogram has a different carrier phase, allowing the signal peaks to be separated along the phase axis. Furthermore, this method can separate the important signals from background noise according to the signals’ frequency characteristics. We describe an experimental demonstration in which three peaks, otherwise masked by noise, are extracted from a low-SNR interferogram.

We assume that the analyzed signal is \( f(z) \). The phase-resolved correlation method separates the important signal and the noise in \( f(z) \) by calculating the discrete correlation between a reference wavelet and the analyzed signal. The reference wavelet is assumed to be

\[
h(z, \phi, \nu) = h_c(z) \times h_n(z, \phi, \nu),
\]

where \( h_c(z) \) is the envelope of the reference wavelet and \( h_n(z, \phi, \nu) \), the carrier of the reference wavelet, is assumed to be

\[
h_c(z, \phi, \nu) = \sin(2\pi \nu z + \phi),
\]

where \( \nu \) is the carrier frequency and \( \phi \) is the phase-bias variable. For application to interferogram analysis, the envelope is assumed to be a Gaussian wave in

\[
h_c(z) = \exp[-\pi(z/\beta)^2],
\]

where \( \beta \) determines the width of the envelope. The reason for this assumption is that the temporal coherence function of a white-light or low-coherence-light source is in most cases a Gaussian function.

The phase-resolved correlation function of \( f(z) \) is defined as

\[
W(n_z/\nu, \phi, \nu) = \int_{-\infty}^{+\infty} h(z - n_z/\nu, \phi, \nu)f(z)dz,
\]

\[
n_z = \ldots, -2, -1, 0, 1, 2, \ldots,
\]

\[
\phi = [-\pi, +\pi], \quad \nu = [0, +\infty],
\]

and \( n_z \) is an integer, making \( W \) a spatial discrete function whose spatial sampling period is \( 1/\nu \). The one-dimensional signal \( f(z) \) is expressed as a three-dimensional, discrete-position phase and frequency...
Now we calculate the phase-resolved correlation of the signal shown in Fig. 1. In this case, to simplify the example, our investigation involves only one frequency. The carrier frequency of the signal is determined by the signal's discrete Fourier-transformed spectrum. The important signals are localized near the carrier frequency, so the two-dimensional correlation includes all the signals except for the noise. We use a Gaussian wavelet with a carrier frequency of $2.3 \times 10^8 \text{ m}^{-1}$ and a width of $\beta = 7 \times 10^{-9}$, as shown in Fig. 2. This algorithm, which is implemented in programming language C on an 800-MHz Pentium III processor, takes 600 ms to calculate a phase-resolved correlation. Figure 3 shows the result of the phase-resolved correlation; (a), (b), and (c) in Fig. 3 correspond to those in Fig. 1. Three peaks appear to be caused by the different beams that are reflected by different depths in the sample because each has a different carrier phase, as shown in Fig. 3. To take the opposite example, these peaks would have the same carrier phase if the peaks were reflected at the same point on the sample and subsequently separated by noise or inaccuracy in the measuring system. The resolution of this method is limited by the broader resolution of the coherence length of the light source or the width of the reference wavelet. The sampling period of the interferogram must be shorter than half of the carrier wavelength, because of the Nyquist theorem.

As we can see from the example shown in Fig. 3, phase-resolved correlation can separate the peaks in a one-dimensional signal into peaks with a three-dimensional distribution, thus permitting their easier identification. Furthermore, the calculation of the correlation has the additional effect of spectral filtering. Hence the correlation separates the important signals from the unwanted noise.

As a more practical example of depth-structure measurement, we analyzed a low-coherence interferogram with a low SNR. The measured sample was an aluminum mirror coated with an 18-μm-thick aluminum oxide layer. Figure 4 is a schematic diagram of the interferometer that we used, which includes a superluminescent diode light source with a central wavelength of 850 nm and a 12-nm spectral width. This interferometer contains a confocal optical setup with lenses L3 and L4 and a pinhole to improve the SNR of interferograms of measurement. The SLD beam is split into two optical paths by the beam splitter. One beam is reflected by a plane mirror and acts as the reference beam, and the object beam is reflected and scattered by the measured sample. These two beams interfere at the photodetector. By scanning the path length difference between these two beams, using a stepping motor, we can obtain a low-coherence interferogram that contains the depth information on the sample as shown in Fig. 5.

This interferogram contains three peaks that are caused by (a) surface reflection, (b) border reflection between the aluminum mirror surface and the aluminum oxide layer, and (c) multiple reflection, but we cannot identify them by conventional analysis because of the low SNR and the close proximity of the peaks. The phase-resolved correlation method is able to improve both selectivity and accuracy of identification. In this case, we analyzed the interferogram at only its carrier frequency for the same reason as in the previous case, so the interferogram can be converted into a two-dimensional distribution on a phase($\pi$)–position(z) plane as shown in Fig. 6, where positive and negative correlation peak pairs, such as (b) and (b'), can be confirmed. Two peaks in a peak pair that are separated by $\pi$ rad should have
Fig. 4. Interferometer for measurement: SLD, superluminescent diode; L's, lenses; M, mirror; BS, beam splitter; SM, stepping motor; PIN, pinhole. The focal length of lenses L2 and L3 is 10 mm. The sample is aluminum covered by an aluminum oxide layer. The stepping motor is driven with a period of 100 nm.

Fig. 5. Unprocessed low-coherence interferogram of the aluminum mirror. Although three signal peaks, (a)–(c), are in fact present, they are masked by noise.

We can identify peak (b) in the center of Fig. 6, and two additional small peaks (a) and (c) to its right and left, all of which have different carrier phases. Hence we can conclude that there are three separate signals that are caused by different reflections in the sample. Signal (a) represents the surface reflection, (b) represents the border reflection, and (c) represents the multiple reflection. This operation allows us to extract three signal peaks previously masked by noise.

We have proposed a new signal analysis method that we name the phase-resolved correlation method. Most methods that were previously applied to interferogram analysis to improve the SNR could separate signals from noise but were not able to separate independent signals. However, by using the phase-resolved correlation method that we propose here, we can clearly identify individual signals. In an experimental demonstration the method showed its ability to identify a thickness of 18 µm and noise-masked interferogram signal peaks. We have confirmed that this method is highly effective for analyzing low-coherence interferograms.

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